

Electron-Positron Annihilation in Solids

“2 Dimensional Angular Correlation of electron-positron Annihilation Radiation”

2DACAR

Spectroscopic tool to study the electron momentum density in solids

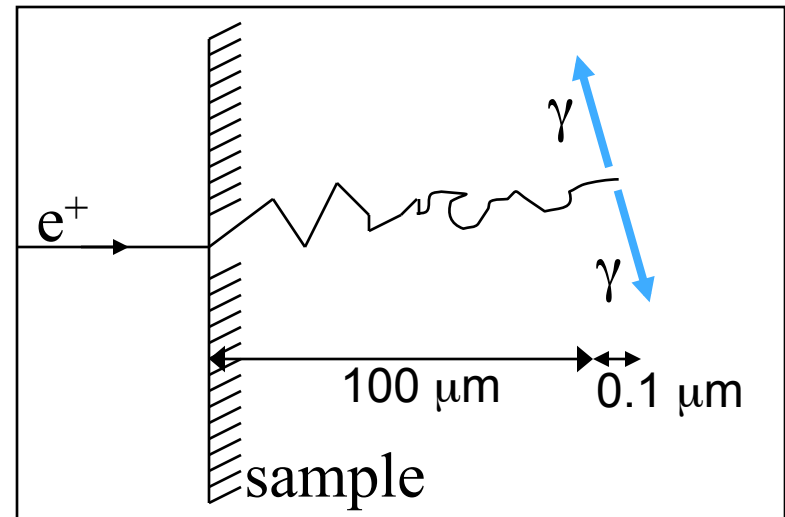
Most often used to determine the Fermi surface of a material.

Experimental idea

High energy (<0.54 MeV) e^+ from a Na^{22} radioactive source bombard the sample

- inside, they quickly (~ 1 ps) lose their energy by scattering and are implanted to a depth of ~ 100 μm

Diffusion length of $e^+ \sim 0.1$ μm , so surface effects can be ignored.

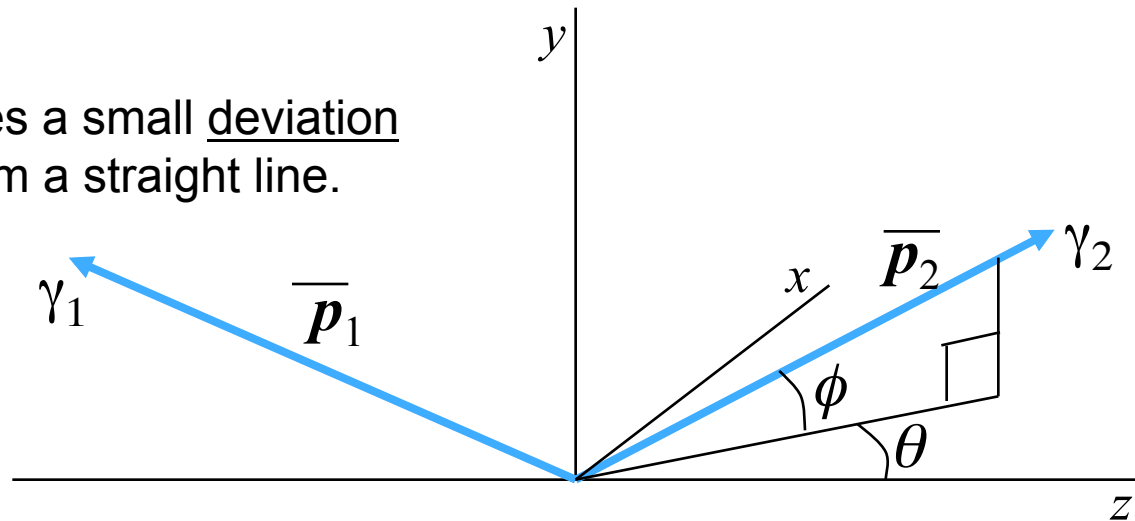


Low source activity and fast annihilation rate
→ one positron in the sample at a time

There they annihilate with \sim zero momentum producing predominantly 2γ 's
(each with energy, $E_\gamma \sim 511$ keV)

Bit of theory

The e^-e^+ momentum causes a small deviation in the photons' direction from a straight line.



This angular deviation can be measured yielding information on the e^- momentum distribution in the sample.

What's the relation expressing energy conservation (neglect KE and PE of e^\pm) ?

$$2m_0c^2 = cp_1 + cp_2$$

If \overline{p} is the initial momentum of the $e^- e^+$ pair then momentum conservation yields,

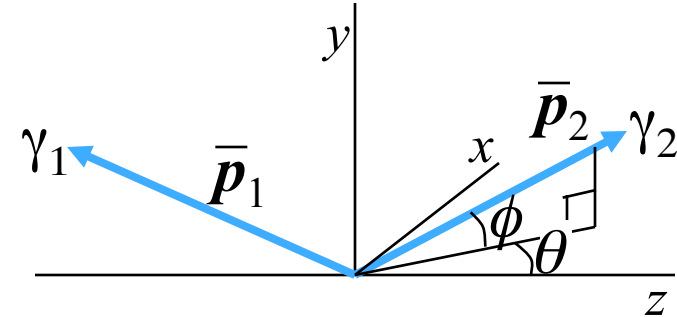
$$\overline{p} = \overline{p}_1 + \overline{p}_2$$

Resolving the momentum into components along x , y and z gives:

$$p_x = (p_1 + p_2)\cos(\varphi/2)\sin(\theta/2)$$

$$p_y = (p_1 + p_2)\sin(\varphi/2)\cos(\theta/2)$$

$$p_z = (p_1 - p_2)\cos(\varphi/2)\cos(\theta/2)$$



Where θ , and ϕ are the angular deviations from anticollinearity.

From the energy equation, $p_1 + p_2 = 2m_0c$.

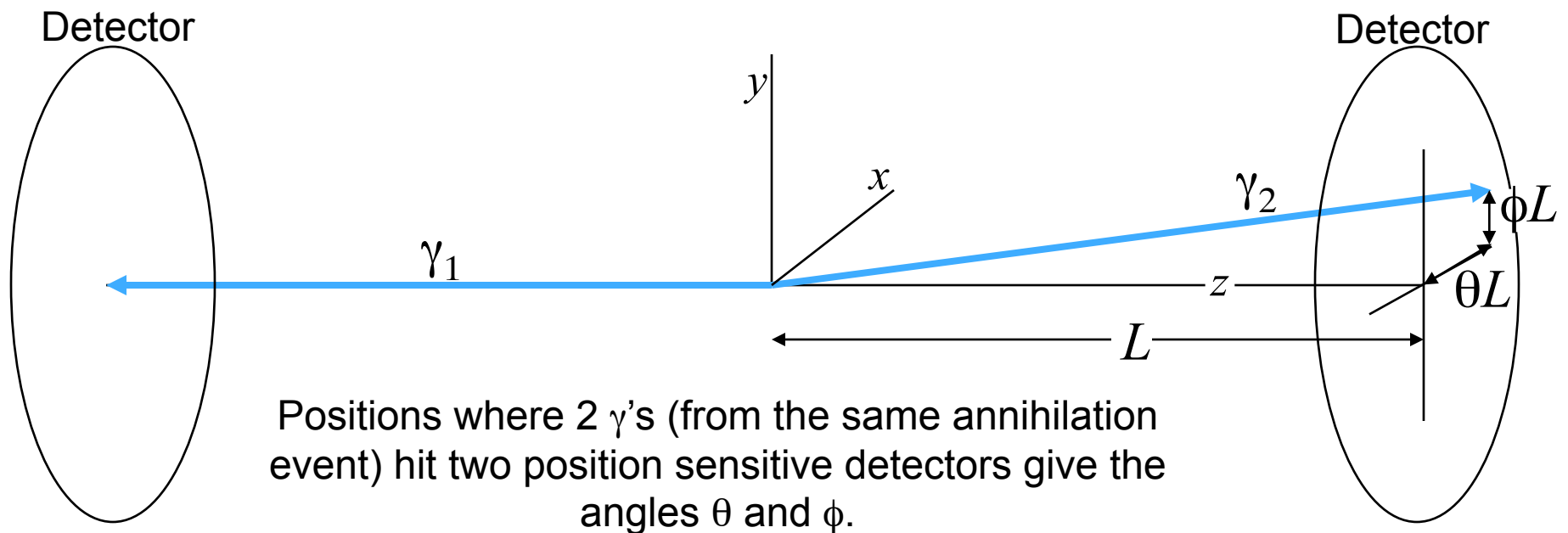
Substituting this into the above equations and taking the small angle limit* gives:

$$\begin{aligned} p_x &= m_0c\theta \\ p_y &= m_0c\phi \end{aligned}$$

θ and ϕ are v. small (~ 10 mrad) because $\bar{p} \ll m_0c$

θ and ϕ are measured in a 2DACAR experiment, yielding a 2D projection of the electron-positron momentum distribution

Note, p_z not measured directly in the expt. because of poor resolution. Instead, several 2D projections can be measured along different directions and the full 3D distribution obtained via reconstruction techniques.



Build up a distribution of $N(\theta, \phi)$

A typical measurement may take several weeks and contain several hundred million counts.

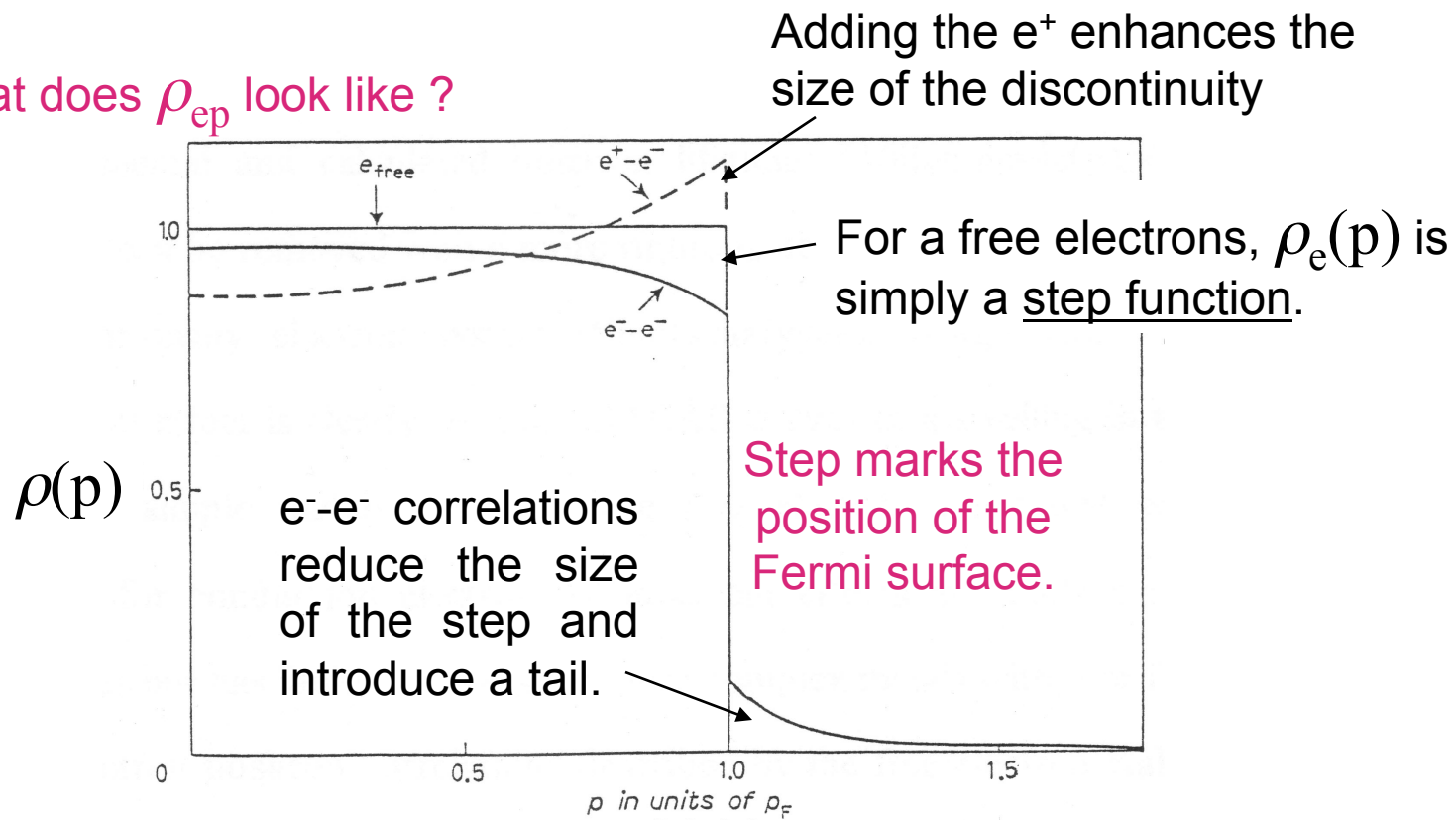
What do we measure?

measurement

$$N(\theta, \phi) \propto N(p_x, p_y) = \int \rho_{ep}(p) dp_z$$

Projection of e-p
momentum density

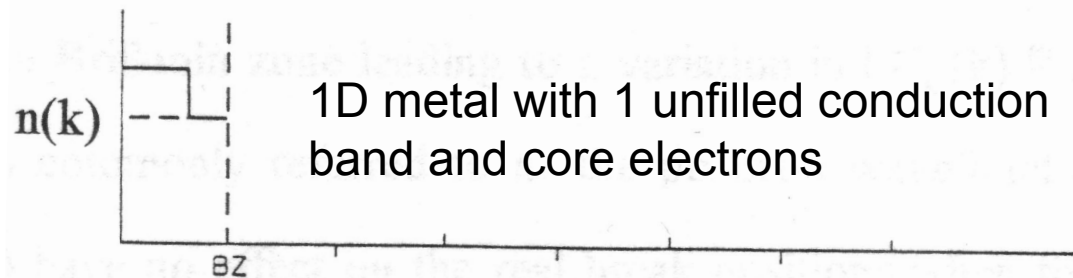
What does ρ_{ep} look like ?



In a real metal, this step functions sits on top of a background due to the core electrons

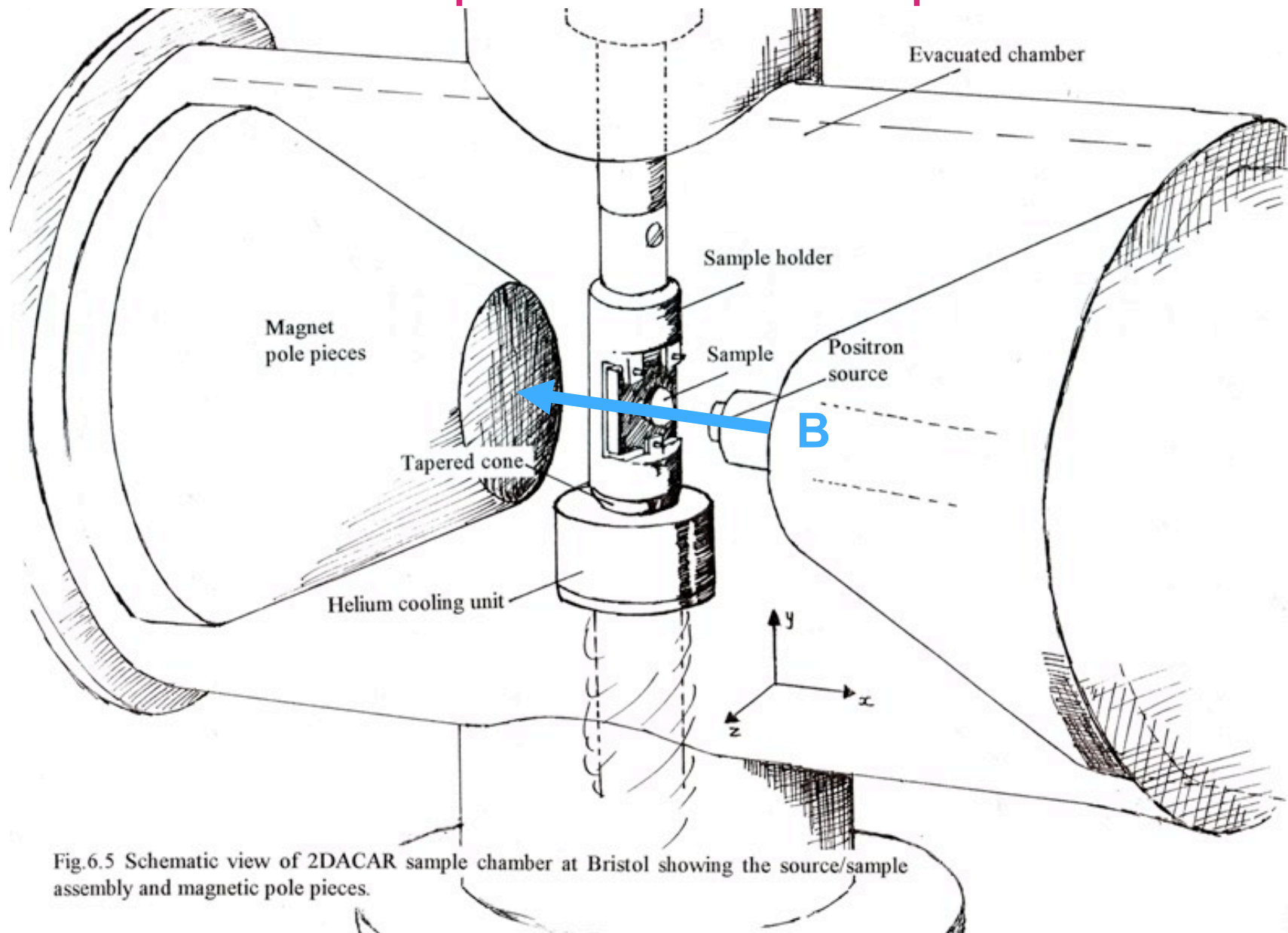
How do we recover the Fermi surface information from this mess?

Use the LCW procedure

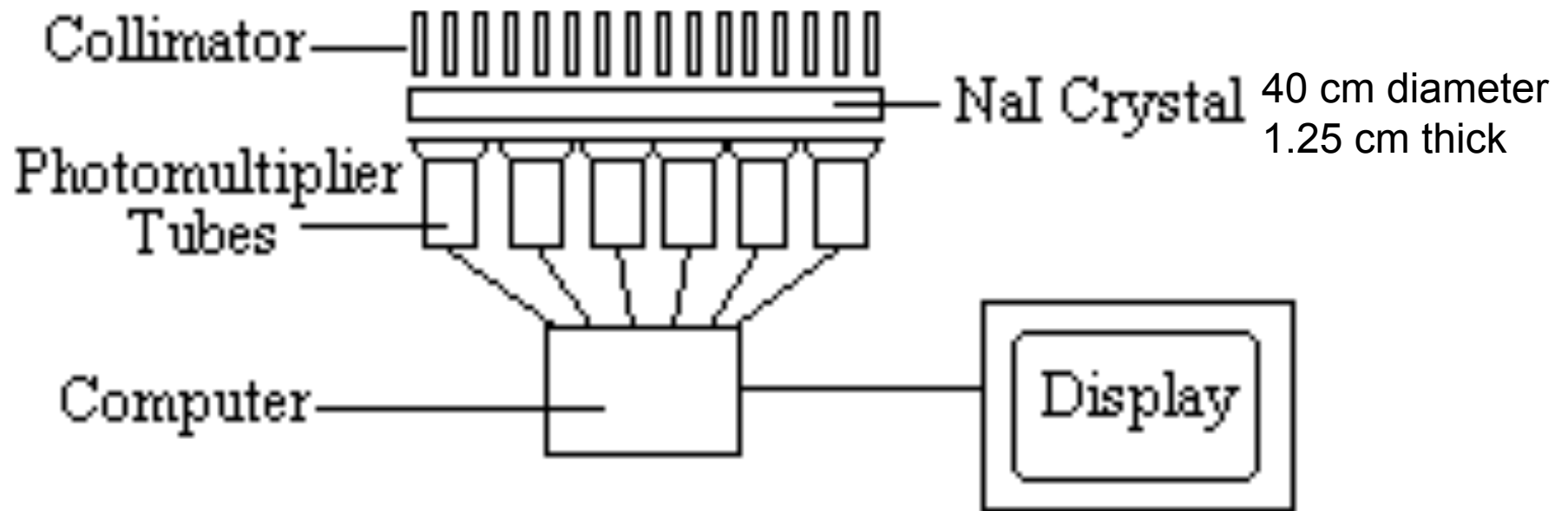


LCW: sums the measured distribution over all reciprocal lattice points. The higher momentum components are folded back into the 1st Brillouin zone and the steps are recovered.

Experimental set up



Position sensitive gamma detector (Anger camera)



Single NaI scintillator optically coupled to 61 PMTs

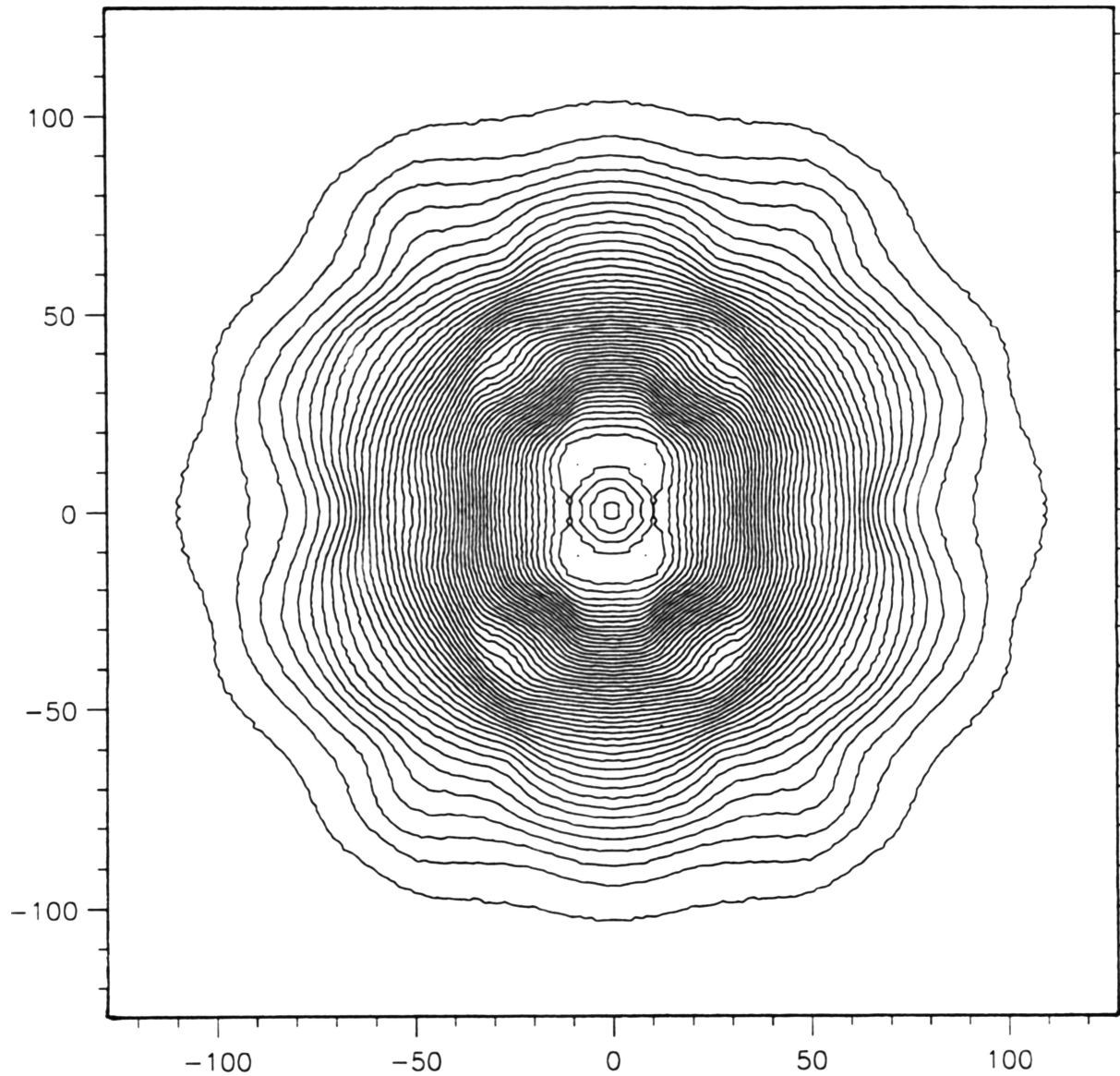
Position resolution of detector ~ 4.2 mm

Detector-sample-detector distance ~ 25 m

→ Angular resolution ~ 0.5 mrad (~ 3 x better ARPES)

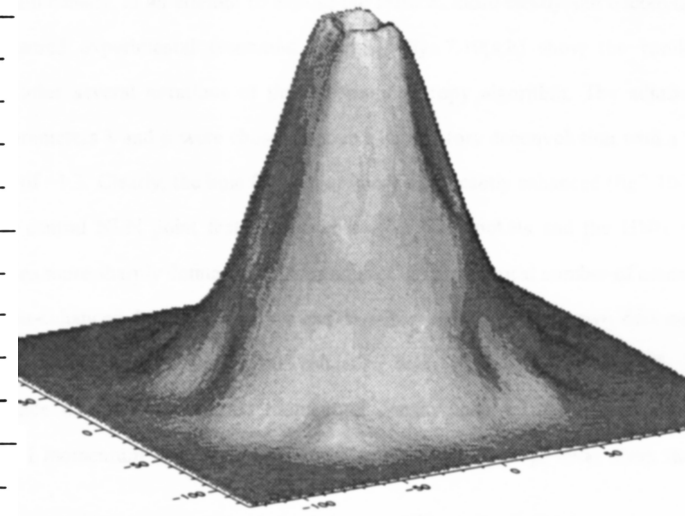
→ Momentum resolution (~ 10 times worse than ARPES)

So what does the data look like?

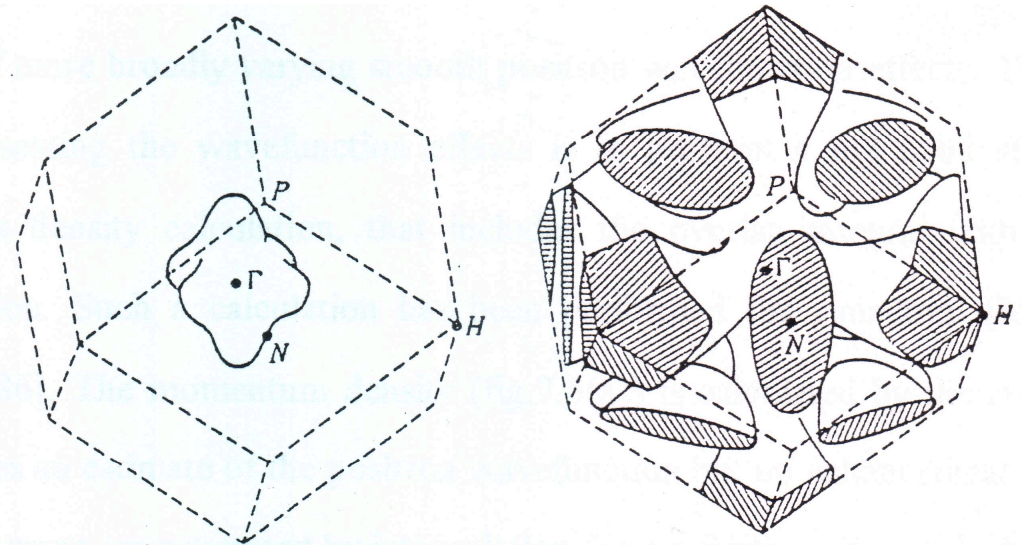
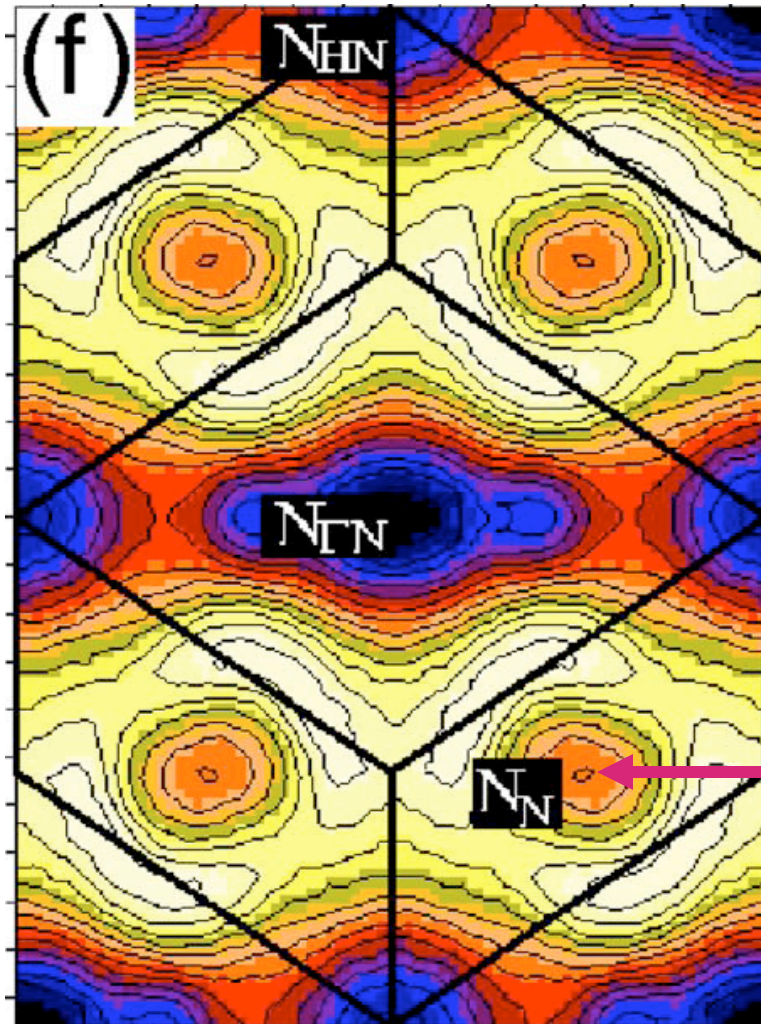


Vanadium

Measured with z along
the $[110]$ direction

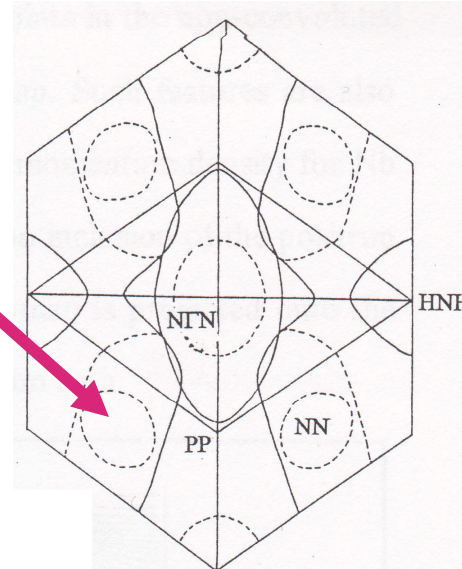


....And after LCW folding



Theoretical Fermi surface of Vanadium

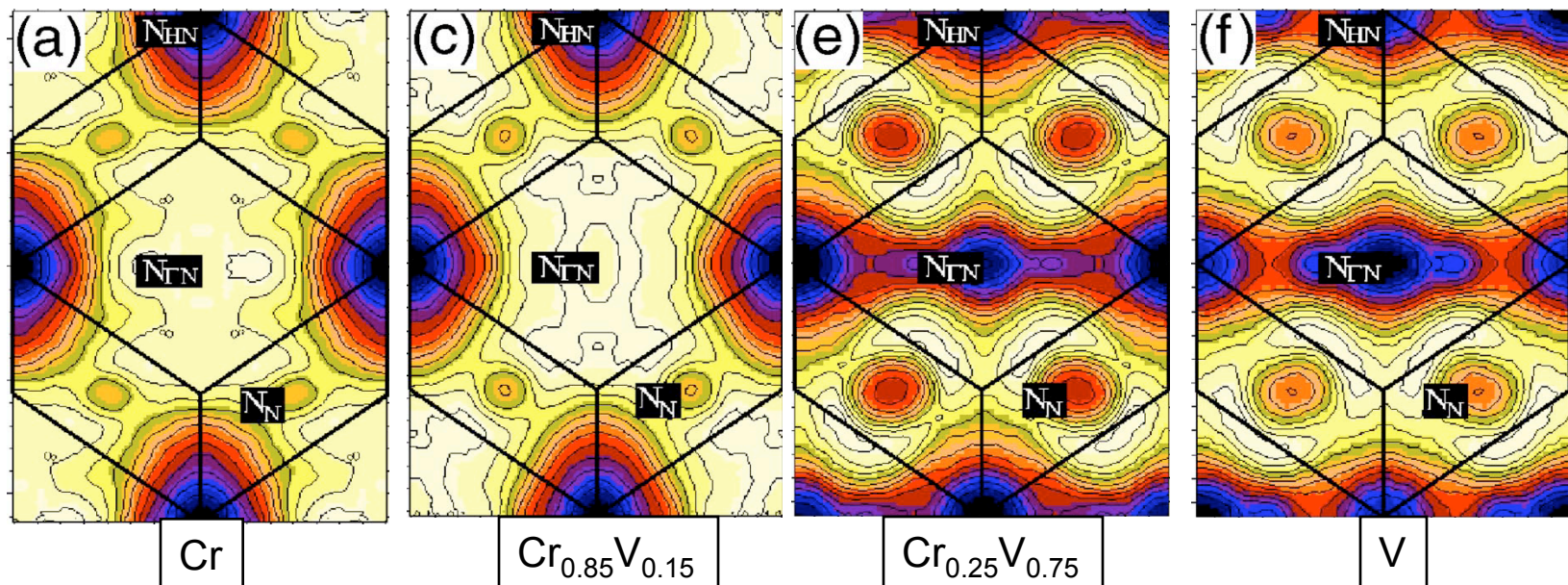
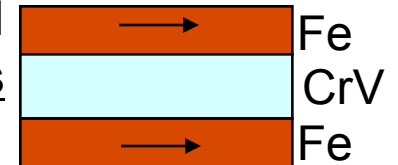
N hole
pockets
project
cleanly



Theory projected along [110]

Giant Magnetoresistance (GMR) in Fe/Cr /Fe and other multilayer systems .

Magnetization vectors in the magnetic layers oscillate between AFM and FM alignments, with a periodicity that depends on the thickness and type of material used in the intervening spacer layers.



The dimensions of the N_N hole pockets mirror the evolution of the oscillatory exchange coupling seen in $\text{Fe/Cr}_{1-x}\text{V}_x/\text{Fe}$ and other multilayer systems.

It is believed that nesting across the N_N hole pocket is responsible for the periodicity seen in the multilayered systems

Reconstruction of the 3D Fermi surface

By measuring several projections of the momentum density, it is possible to use reconstruction techniques* to generate the 3D Fermi surface

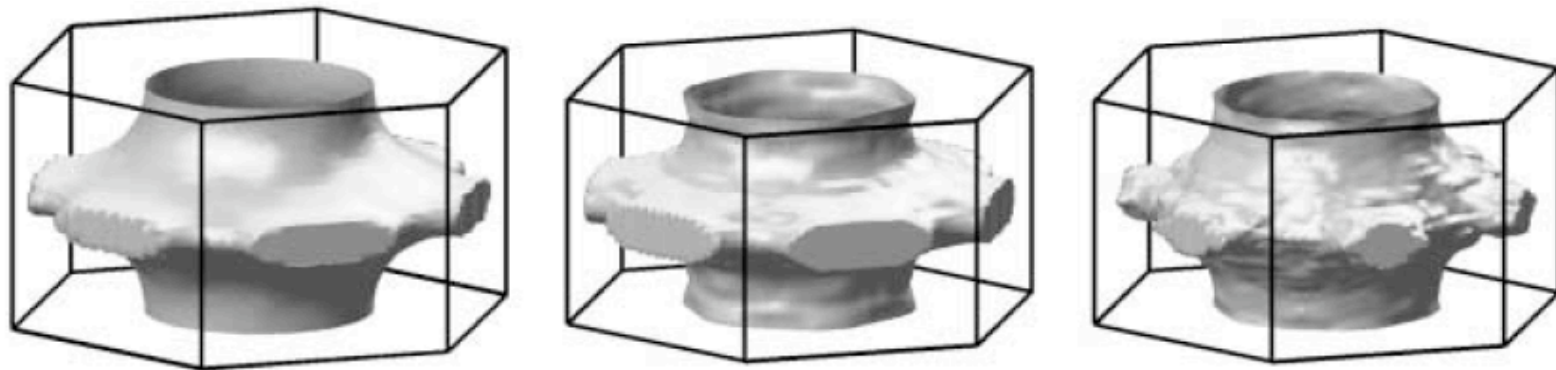


Fig. 6 – Positron annihilation measurements of the FS topologies in pure Y (left), $\text{Gd}_{0.62}\text{Y}_{0.38}$ (middle) and $\text{Gd}_{0.70}\text{Y}_{0.30}$ (right).

S.J.Crowe et al, *Europhys. Lett.* 65 (2) 235 (2004)

* A.M. Cormack, J. Appl. Phys. **34**, 2722 (1963); **35**, 2908 (1964).

Does 2DACAR work well for all materials?

Not always. We measure the electron-positron momentum density. $\rho_{ep}(\mathbf{p})$

The positron is positively charged so it is strongly repelled from the positive ion cores in a metal and preferentially annihilates with the outer valence electrons (which is good)

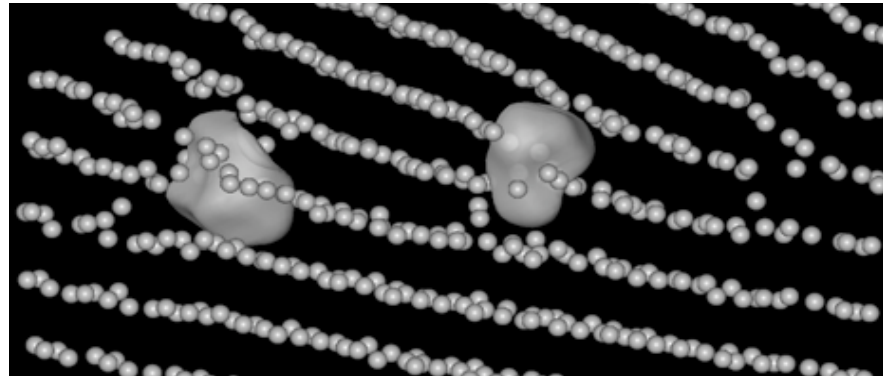
But, if the positron wavefunction doesn't overlap uniformly with these electrons
→ smoothly varying modulations in the data ("positron wavefunction effects") – Bad

Generally speaking, the positron “sees” s and p -like electrons more than d and f

Technique works well for simple metals like Cu,
- reasonably well for transition metals and
- poorly in high T_c superconductors and other novel materials.

Does 2DACAR work well for all materials?

Also, the positron is very sensitive to vacancies and other defects where it becomes 'trapped' in the region of low electron density.



Positron wavefunction at two vacancy-like defects at a grain boundary in nanocrystalline Ni, S. Van Petegem et al

The advantages of the technique are that it can measure

- at high temperature
- and in disordered alloys (unlike dHvA)
- the bulk - It is not surface sensitive (unlike ARPES)

The disadvantages of the technique are that

- it measures a projection of the momentum density and Fermi surface
- positron wavefunction effects can mask the Fermi surface signal
- it has poor momentum resolution compared to say ARPES or dHvA
- it is sensitive to point defects.